A NEW WAY TO DESIGN SOFTWARE FOR INDUSTRIAL AUTOMATION - 3D PRINTER CEMENT MIXTURES

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This paper presents a new way of developing machine software for the automation industry. This example focuses on a 3D printer intended for printing cement mixtures. The mechanical and electrical construction is shown for clarification. New mappTechnology by a company called B&R is explained, highlighting its benefits t for software developers. Both the advantages and disadvantages are discussed at the end.

KEYWORDS

software design, mapp, automation, 3D - printer, cement, cnc control

1 INTRODUCTION

Throughout history people have tended to replace hard physical labour with machines, increasing productivity and making employees work easier. This trend seems to be continuing, with the presentation of Industry 4.0 at the EMO in Hannover in 2013. [Cheng 2016]. Factory owners are tending to invest more in technology and, with that, the role of manual labourers is slowly decreasing. Some working positions may disappear. However, others will emerge, as industrial revolutions have shown many times in the past.

Recent industrial goals have focused mainly on achieving mass production and the importance of collecting real time information about the production process was put aside. Even though there are trends in software development for industrial processes and applications [Lee 2018], when compared to software development in IT or smartphone industries, software development in the manufacturing industry still lags behind. Nevertheless, the combination of applications and background operations, the use of the internet of things [Donzia 2018], [Rafique 2020], [Tzanahua 2020] and collecting large amounts of data [Gokalp 2016] are becoming modern ways of achieving Industry 4.0 [Azarmipour 2019], [Gorecky 2014].

The aim of this paper is to take the first step in the automation of construction processes by implementing the technologies and principles of Industry 4.0 into the construction industry. Automation of this industry seems to have been left behind, but the idea of a 3D - printed building has raised interest in this field, and has now led to the development of new technologies and building materials. The machine controlled by the presented software in this paper helps with the development of fast solidification cement-based mixtures [Wolfs 2019], [Le 2012], which can be used for the 3D - printing of buildings. New shapes of walls can be created while their structural properties can be tested.

2 TESTBED FOR PRINTING BLOCK SAMPLES

Testbed is a 3-Axis CNC gantry machine (see Fig. 1 and 2) which is used in the development of cement-based mixtures which can be used in the building of multi-storey buildings. In this chapter, the mechanical, electrical and safety parameters of the Testbed are described.

2.1 *Mechanical parameters of the Testbed*

The requirements for the Testbeds workspace (see Tab. 1) were determined as (X/Y/Z) (3500 / 1100 / 1300) mm, based on the space available for Testbed. Such workspace is sufficient for the development and verification of simple 3D printed elements. Based on the requirement of the working space, easy access to the print head placement and the experimental use of the interior, we designed the Testbed as a gantry CNC machine. This solution allows free movement of the print head throughout the workspace and there is no risk of collision with already printed parts of the product due to access of the print head from above.

Figure 1. Model of Testbed for development of cement mixtures

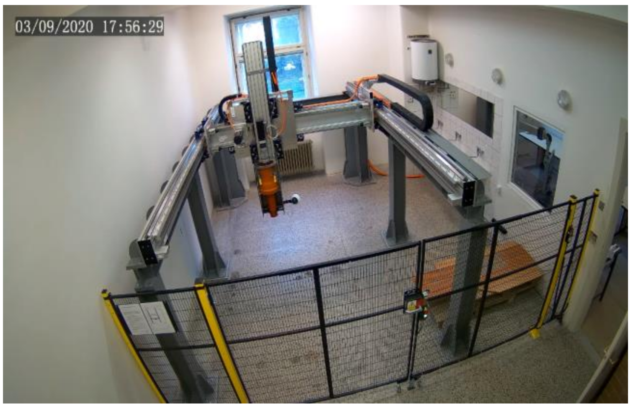

Figure 2. Testbed with print head and fence with safety lock

Following on from the experimental development of the print head (see Fig. 3), we designed Testbed for handling a payload of 150 kg based on initial mass estimates. Testbed is designed to achieve sufficient dynamic capabilities to enable the development of new technological approaches to the 3D printing of cement based mixtures. Even with a relatively heavy load, in the X/Y plane it is able to achieve a speed of) 3 m/s (see Tab. 1 and an acceleration of y = 4 m/s². Therefore, it will not restrict users developing fast printing techniques. We believe that the ability to develop technology for fast printing distinguishes our approach from that of other cement-based mixture 3D printing systems.

Parameter	X	Y	Z
Workspace[m]	3,5	1,1	1,3
Max velocity [m/s]	3	3	2
Acceleration [m/s²]	5	4	3
Repeatability [m]	$\pm 2*10^{-4}$	$\pm 2{,}5*10^{-4}$	$\pm 2{,}5*10^{-4}$
Accuracy [m]		$< 10^{-4}$	
Max. load weight [kg]		150	
Testbed weight [kg]		3920	

Table 1. General parameters of Testbed

Figure 3. First generation print head of the Testbed

The CNC machine consists of four Cartesian axis linear modules by Rollon GmbH. The support for each axis is a heavy duty extruded and anodised aluminium profile. These are made from hardened and tempered aluminium alloy AL Mg Si 0.5. This solution has great benefits for the experimental equipment, with the possibility of the easy attachment of other accessories if required. The main carriage plate is made of a high-performance casting alloy, which rolls on trapezoidal guides and it is driven by a rack and pinion drive with helical teeth. This makes the modules capable of positioning with an extremely low margin of error and suitable for high dynamic performance with heavy loads. Similar modules are often used in cement production and are thus suitable for work in such demanding conditions. Therefore, it is fully compatible with our 3D printing application. The Cartesian axis system is mounted on a steel frame consisting of welded and screwed parts with six supports. The weight of the entire Testbed is 3 920 kg. The Z axis is formed by an aluminium profile moving vertically. . Standardized grooves throughout the profile allow almost unlimited installation options for the developed print heads.

2.2 *Control and drive systems of the Testbed*

Permanent magnet synchronous motors were chosen for positioning in the cartesian workspace. All drives are controlled by safety servo controllers and the accuracy of positioning is achieved by absolute encoders, which always provide the actual position in the workspace so the homing procedure can be done from any position without any movement. This can save some time at the initialization of Testbed and the system can be re-initialized after error, allowing the machine to continue where it stopped without homing to the reference position.
Axis X consists of two linear modules. Usually one drive is sufficient to control this type of system but, due to the heavy payload and quick dynamic changes, linear module crossing forces had to be taken into consideration. Therefore, two servo drives, one on each linear module, have been used. This solution prevents the possibility of mechanical issues during rapid dynamic changes in the axis X plane. The detailed specification of motor and gearbox parameters are shown in Tab. 2.
Testbed is controlled by an industrial computer, APC910, with an installed hypervisor, allowing it to run a real-time operating system (automation runtime) and a general operating system (Linux or Windows) simultaneously. The general operating system allows us to design models of building blocks and convert them into CNC programs (G-code), which can then be run by the real-time OS automation runtime. The general operating system can also serve as a gateway to IoT in the way that it can transfer data from the real-time system into OPC UA server or cloud.

Axis	Type	Description
X	Motor	PMSM, TMax = 14,4 Nm, IMax = 10,6 A, nMax = 6 029 rpm, TRms = 2,98 Nm
X	Gearbox	Planetary Coaxial, T2Max = 131 Nm, n1Max = 7 000 rpm, i = 5:1, 97,0% Efficiency, J = 1,343e-4 kg*m²
Z	Motor	PMSM, TMax = 38 Nm, IMax = 36,5 A, nMax = 5 336 rpm, TRms = 7,84 Nm
Z	Gearbox	Planetary Coaxial, T2Max = 736 Nm, n1Max = 5 500 rpm, i = 20:1, 96,0% Efficiency, J = 0,0011183 kg*m²
Y	Motor	PMSM, TMax = 38 Nm, IMax = 36,5 A, nMax = 5 336 rpm, TRms = 8,25 Nm
Y	Gearbox	Planetary Coaxial, T2Max = 131 Nm, n1Max = 7 000 rpm, i = 5:1, 98,0% Efficiency, J = 4,76e-5 kg*m²
E	Motor	PMSM, TMax = 14,4 Nm, IMax = 10,6 A, nMax = 6 029 rpm, TRms = 3,4 Nm
E	Gearbox	Planetary Coaxial, T2Max = 192 Nm, n1Max = 5 500 rpm, i =16:1, 94,0% Efficiency, J = 0,5 kg*m²

Table 2. Testbed motor and gearbox parameters

2.3 The Testbed Safety features

All machines produced in the EU must be equipped with safety features that protect users against injury. Our machine is not intended for the open market but rather for serving as laboratory equipment to be used for testing. However, we

implemented some safety features in our machine even though, in this case, it wasn't mandatory.
The first, simplest, user protection is a locked fence. (see Fig 2). This protects the working area from random access during the concrete printing process. The fence is equipped with a safety lock which is compliant with safety standards. The machine also has two separate emergency stop circuits with a two-channel connection (see Fig. 4).

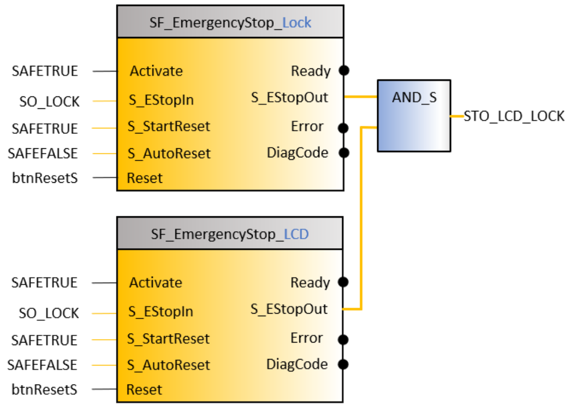

Figure 4. Safety feature emergency stop implementation

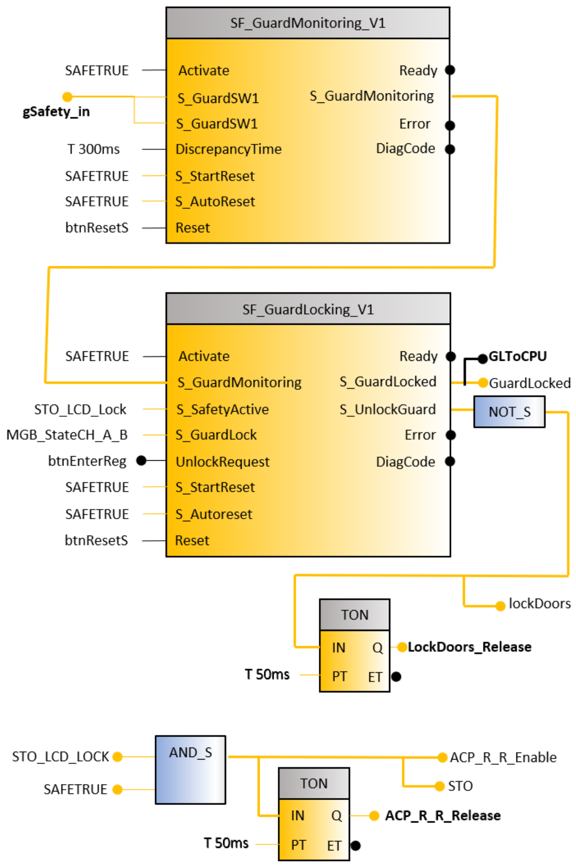

Figure 5. Safety feature lock doors implementation

When an operator wants to enter the Testbed working area, he or she must ask for the lock to be opened. This is possible when the machine Isn't printing. If a user needs to operate the axes of the machine with the fence open, then the SLS (Safety Limited Speed) function is active to avoid dangerous situations. It is not possible to print any shapes using CNC from cement mixtures in this state. The door lock safety circuit is shown in Fig.5.
If some dangerous or unintended situation emerges during running time, then any emergency stop button can be used to apply the STO (Safe Torque Off) function (see Fig.6). The safe state for our machine is to have the power stages of all servo motors switched off. In this case the operator has to deal with the issue and acknowledge the error on the control panel to return to Testbed's operational state.
We used SafetyDesigner by B&R to implement the safety features mentioned above. This software is a part of Automation Studio and the safety software is key to all other programmes in Automation Studio. Thanks to this configuration, data can be sent between the user application and the safety application very easily. This is particularly true for SLS functions and some other supplementary signals.

3 NEW WAY OF SOFTWARE DEVELOPMENT

Precision and speed of manufacturing were the most important demands at the beginning of the automationrevolution.. Therefore, the main focus was on s improving hardware such as drives, gears, encoders, sensors and control units. The control software for each machine was mostly developed by a programmer from the outset as there were no tools which could make software development easier. Recently, the possibility of producing hardware very cheaply and effectively due to high demand, and the demands of collecting data from manufacturing processes, increased the importance of software development [Schutz 2013]. This process led to the simplification of coding for each specific machine and programming became closer to playing with building blocks and setting parameters rather than writing complex codes.

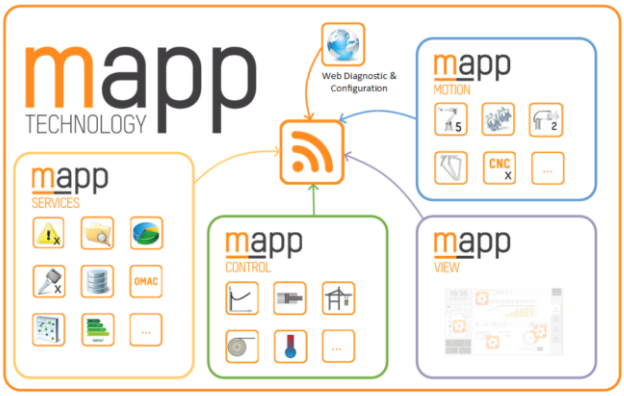

Figure 6. mappTechnology concept

The Austrian company B&R, which is a member of the ABB group, developed a system called mapp (modular application) Technology (see Fig. 6). "This is revolutionizing the creation of software for industrial machinery and equipment. **mapp components** – mapps for short – are as easy to use as a smartphone app. Rather than write lines and lines of code to build a user management system, alarm system or motion control sequence from the ground up, developers of machine software simply configure the ready-made mapps with a few clicks of the mouse. Complex algorithms are easy to manage. Programmers can focus entirely on the machine process" [B&R 2020].
The main idea of mappTechnology is to use various mapps (motion control, data collecting, HMI) and connect them in the background through mplinks. The mapps communicate with

each other directly or via the OPC UA server in the PLC, transfer data and if necessary, execute commands received from other mapps. In this way, most common problems such as axis or cnc control, error handling, multi-user control or data collecting are covered and programmers can focus on the specific control tasks of a required machine or process. This method of software development reduces time and costs when developing a new series of machines, production lines or specific task machines not commonly used in industry, such as our Testbed. The emphasis with mapps is on flexibility, scalability, quality and an easy-to-understand interface.

The LIAM institute made a study [LIAM 2015], where the development times of two flying saw softwares were compared. The first method of software development used mappTechnology while the second used standard PLCopen blocks. The study claims that using mappTechnology increased time-efficiency by two-thirds. Therefore, we decided to develop software for Testbed using mappTechnology and then compare it with our experience with software development using PLCopen blocks.

4 TESTBED CONTROL SOFTWARE DESIGN

MappTechnology was used as the basis of our Testbeds control software, consisting of three layers - motion control, software control in PLC and HMI. The connection between the layers and the mappTechnology architecture is shown on Fig. 7.

4.1 *Mapp Motion - motion control of the testbed*

Motion control is provided by mapp Motion. Each servo-motor is represented by mapp MpAxis which is an axis configuration with a set of axis parameters such as axis limits, init parameters and homing type procedure.

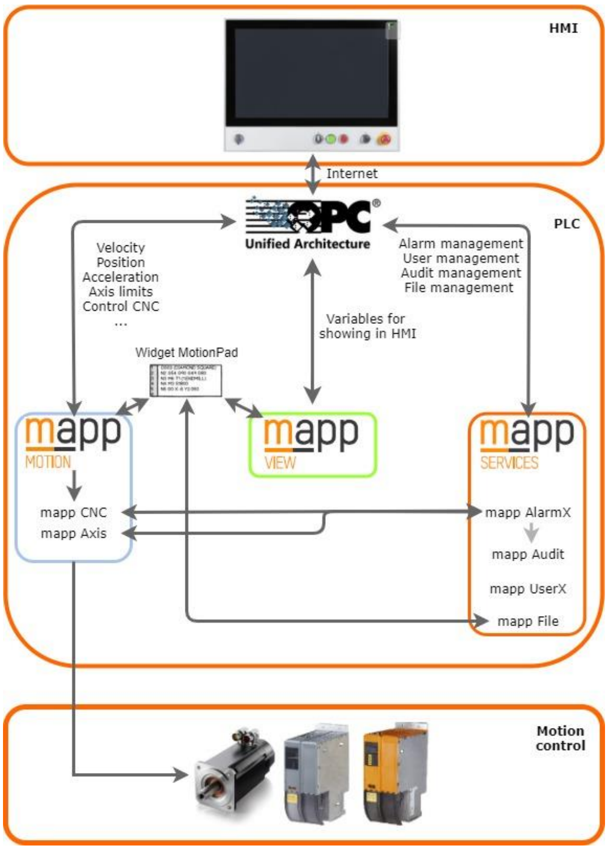

Figure 7. Mapp technology architecture used in Testbed

The MpAxis also contains MpAxisBasic (see Fig. 8), which is a function block for axis control. Also, each axis has a mplink parameter, which is used as a reference (similar to pointer) to the controlled axis. The mpLink can be connected to other Mapps and can communicate with them in the background or receive and send commands if necessary. Mapp Motion contains MpAxisBasic and MpCnc function blocks for manual motion and CNC control of the Testbed. MpAxis is used for the initialization and manual control of each axis. If there is an error, it gives us information about the error and the error can then be removed by the ErrorReset command. MpCnc binds all axes into an axis group and controls them as a CNC system. It also collects data from each axis through MpLink (similar to pointer) and controls them according to G-code instructions.

4.2 *Mapp Services - data handling and communication*

Another important group of mapps in the control software is mapp Services which can operate services such as mapp Alarm, mapp User and mapp Audit for alarm handling, multi-user control and log of software user control operations. Mapps parameters are stored in the OPC UA server in the PLC. From there data, parameters and commands can be accessed by multiple mapps or another PLC.

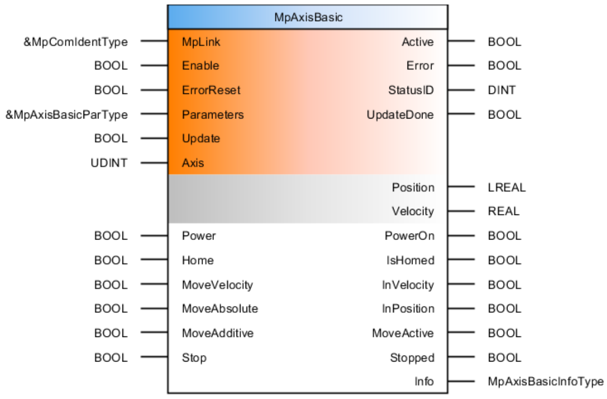

Figure 8. Mapp axis - MpAxisBasic function block

4.3 *Mapp View - HMI for user control of the testbed*

Mapp view uses data in UPC UA and connects them with HMI in the control panel (see Fig 9.) so the Testbed can be easily controlled by an operator. HMI can be also accessed and controlled via an internet browser.

Figure 9. Control panel with HMI

It means that multiple users with different roles can be logged into HMI at the same time and be present on different pages. This option is provided by mapp User. In our software, control of HMI is divided into three roles.

Mapp view also uses a set of widgets which can control multiple Mapps depending on the functionality of the widget used. For example, the widget "motion pad" uses "mapp file" for loading G-codes from a file or an USB device. After loading G-code, the same widget has access to mapp CNC and can control CNC motion.

Another useful widget used in our software is the Alarmbox which reads the alarm log of each axis connected by MpLink. If an alarm is triggered it shows the alarm to the user and when the error is removed and acknowledged it marks the error as solved. It would be more convenient if the widget could reset occurred errors automatically, but each alarm or error requires a different solution, so it is better for a programmer to decide how to react to each error which might occur.

4.4 *Comparison with PLCopen blocks*

When developing software by PLCopen blocks with ARNC0 and APC10 libraries, each axis has to be initialized, powered and homed separately. Creating a CNC system is possible, but adding Axis into the CNC is rather complex as well as connecting axes in order to be able to work as a CNC system. Errors can be read from the axis but each alarm has to be programmed and put into an alarm box manually which complicates error handling. PLCopen blocks do not provide widgets which could be linked to functions or variables. Therefore, component functionality in HMI has to be programmed manually.

When using mappTechnology, all axes can be set into AxisGroup and initialized together. There is an MpLink between Axes, CNC system, alarm system and HMI. When connecting an MpLink from mpCNC with a widget for CNC control, the widget gets access to CNC functions and g-codes can be run without programming a single line of code.

Developing software using mapps is more about the configuration of parameters and connecting function blocks with MpLink, allowing interaction between them. This feature simplifies the development of most of the essential parts, allowing a programmer to focus more on developing the specific control tasks of machines or processes.

When developing software using mappTechnology, malfunctions or improper behavior of mapp components can occur. Mapps are like black-boxes, programmers cannot see inside, so, if anything happens, they cannot fix it themselves and have to consult with B&R support. Malfunctions within older PLCopen block software solutions were usually caused by holes in the code and could be debugged and fixed by the programmer himself.

5 G-CODE PREPARATION FOR 3D PRINTING

The print head path control strategy is based on a CAD model of the printed object. It is assumed that the concrete wall will most often be printed only on the width of nozzle diameter, i.e. only one perimeter. In this case, the easiest way to design 3D objects is as surfaces, where the modelled shells are the middle surfaces of the future object walls.

In the current phase of development, and also concerning the control of the building statics, it is assumed that the internal filling walls will be constructed by the architect in the same way, i.e. they will not be calculated automatically. The 3D model of the object to be printed is therefore created only by surfaces of zero thickness, which together do not close the resulting volume.

However, this presents a problem with the preparation of a G-code for controlling the movements of the print head. Existing slicers such as Slic3r [Slic3r 2018], PrusaSlicer [PrusaSlicer 2020], CuraEngine [CuraEngine 2020], etc. cannot be used. These programs are primarily prepared for 3D models designed as solids and the preparation of print data from the surfaces without any thickness is at least problematic, in many cases impossible.

For 3D printing concrete as a semi-liquid material cured by a chemical reaction, it is necessary to respect other limitations in the way the print head is controlled. Applying a new layer of this material to a previous layer which hasn't hardened yet is problematic. There is a risk of deformation, and thus an inaccurate printout of the wall, due to gravity. Therefore, it is necessary to control the deposition of the material so that the already applied material has enough time to harden.

Also, it is necessary to minimize the length of print head travel when the material is not extruded. During this time, the building material spontaneously flows out of the nozzle. On the one hand, it pollutes the building space, on the other, this material is missing at the beginning of the next printed area. Furthermore, it is advisable to control the movement of the nozzle outside the already printed object, so that there is no risk of deformation and destruction of already printed walls.

It can be seen that 3D printing from concrete and similar materials has many limitations which have to be respected. The optimisation of the print head movement leads to multi-criteria optimization, which will be the subject of further development. Two programs are currently being developed to calculate the print head movement strategy. The first program opens only 2D curves as a single layer pattern. This pattern is repeated in all specified layers, but the movement of the head is calculated with respect to the above-mentioned criteria. The second program is used to generate the print head paths from 3D surfaces representing the middle surfaces of the printed walls in the STL format, see Fig. 10. Here, only the requirement for the minimum length of travel of the print head is respected.

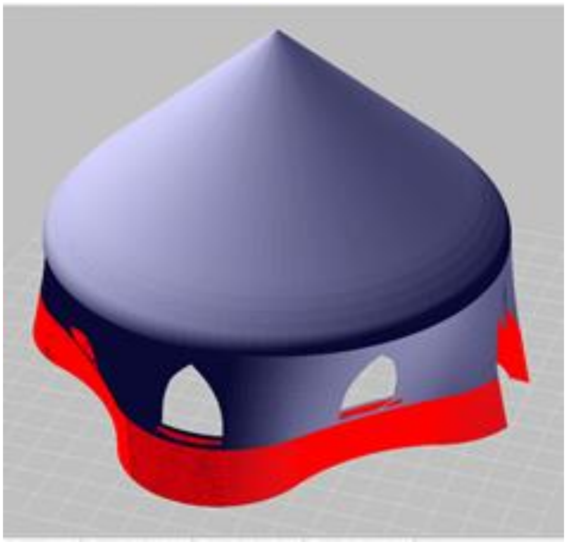

Figure 10. Slicing of STL object in the StarSlicer software

6 RESULTS

Our team developed control software based on mappTechnology within two months. We did not exactly measure how long it took to develop the software, but developing similar software for a 5-axes plasma-beam machine, with ARNC0 and ACP10 functions, took us around five months.

This means using mappTechnology has real advantages as a new means of developing software. For verification of the CNC control, a G-code of a wall sample was generated and we first ran printing tests using a base printing cement-base mixture. As for the sample, we used a rectangular base with a sinus-line filled model. This pattern has a solid strength and thermal characteristics and therefore we are planning to use it as one pattern for printing buildings from concrete. We were able to design a model, translate it into G-Code and run it, using one industrial PLC with a hypervisor.

The extruder output is controlled by the thickness of the printing material and the velocity of the extruder axis, which changes its velocity according to the velocity of the CNC system. The ratio of extruder axis velocity, extruder diameter and material thickness are a subject of further research.

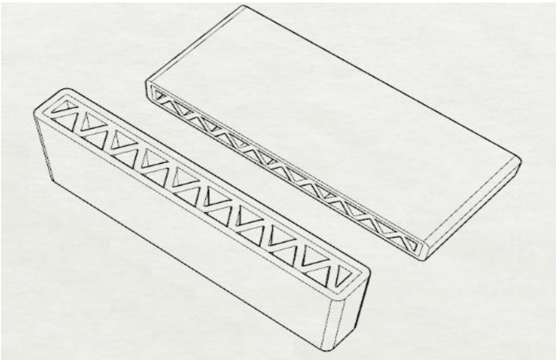

Figure 11. Model of pattern used for 3D printing

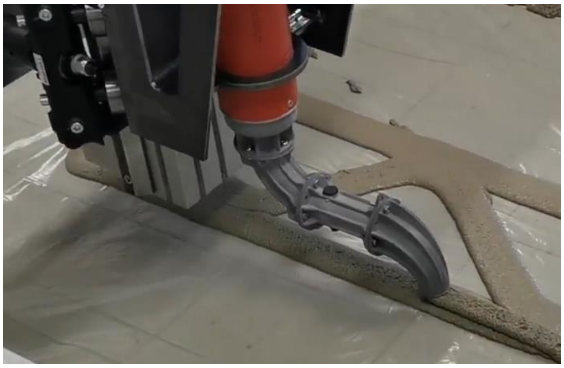

Figure 12. Test of 3D printing with pattern

Figure 13. Printing of chair sample

Since the printing material spills after printing, we were not able to verify the precision of printing with an error of up to 0,1 mm during printing. Nevertheless, even an error of up to 1 mm would be sufficient - precise measurements in 0,1 mm scale are not relevant to our case. Pattern and first printing tests are shown on Fig. 11 and Fig. 12.

A simple CNC program for printing chairs from concrete was developed (see Fig. 13). The sample will be used for further material testing and the results might also give us feedback on how to improve control software and generate G-codes.

7 CONCLUSION

The aim of this paper was to present the control software for Testbed, a CNC machine for printing blocks from concrete. This is an initial step in the further development of a suitable printing cement mixture for use in the 3D printing of multi-storey buildings. This involves the printing of many samples, testing their speed, testing their quickness and quality of solidification and hardening and resolving problems which may occur with printing cement mixtures.

We tested a new way of developing software for Testbed with mappTechnology. This development was a fast and easy way of creating the code for our application. We saved a lot of time developing user management, audit system and CNC system handling. Certainly, the development was more about the configuration of mapp components than writing the software manually. There were many pre-prepared function blocks or widgets that allowed us to create our own software for controlling the CNC machine which tests the cement mixtures. This way of software development does not tie the programmer to developing control software for predefined machines or systems and gives him an opportunity to code programs at his will and implement them into control software. Therefore, mappTechnology can be used for the development of much more complex control software used in connection with uncommon machines or processes.

On the other hand, this system does not allow for the configuration of many details that were accessible in the old way of programming with ARNC0 and ACP10 libraries. We had to learn a new technology which is still under development and some problems had to be solved with the manufacturer's help. For example, lags during CNC motion, the sudden malfunction of "motion when reading USB or MpAudit, which did not correctly record information. Mapps are like black-boxes so we could not solve these problems without support from B&R. Finally, we were able to finish our task satisfactorily and our machine now serves its intended purpose. We would choose mappTechnology again for our next project. We are now aware of all its advantages and disadvantages.

We plan to add a tangential axis to control the rotation of the nozzle so that it can rotate in accordance with the direction of the CNC movement. This feature will allow us to use and test a variety of different nozzle shapes. Another future focus is on the further development of G-code with respect to requirements for 3D printing from concrete.

Basically, this article was not about improving the movement of a CNC system. The quality of the positioning movement, or improved dynamics, are not improved by using mappTechnology. We wanted to compare two ways of software development, not improve any of the parameters of the Testbed. The quality of movement is thought to be the same for both mappTechnology and ARNC0 - the motor hardware, feedback and servo controllers are the same.

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